EFFECTS OF SPACECRAFT LANDINGS ON THE MOON.

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Introduction: The rocket exhaust of spacecraft landing on the Moon causes a number of observable effects that need to be quantified, including: disturbance of the regolith and volatiles at the landing site; damage to surrounding hardware such as the historic Apollo sites through the impingement of high-velocity ejecta; and levitation of dust after engine cutoff through as-yet unconfirmed mechanisms. While often harmful, these effects also beneficially provide insight into lunar geology and physics. Research results from the past 10 years is summarized and reviewed here.

Soil Erosion Rate in Lunar Conditions: The erosion rate of lunar soil beneath a supersonic, rarefied rocket exhaust plume in lunar gravity is difficult to predict. It occurs in a spatially limited annulus that prevents saturated transport via saltation, the case most-studied for sedimentary geology. Experiments to scale unsaturated erosion rates have been performed for the lunar case including: small scale, subsonic jet/soil erosion experiments in the lab; similar experiments in reduced gravity aircraft; similar experiments in large vacuum chambers; supersonic erosion experiments in large vacuum chambers; sandblasting experiments with a hypersonic gun for comparision with Surveyor III impingement damage; field tests in a relevant geological setting on Mauna Kea; and lunar simulant optical density experiments for comparison with Apollo landing videos. Piecing these together produces an erosion scaling relationship for regions of the plume where the Knudsen number relative to a sand grain diameter is small, i.e., Kn<0.01,

$$\dot{m} = U \frac{\rho_s \tau}{\rho_s g d_{80} + c} ,$$

where $\dot{m}$ is mass of soil eroded per square meter per second, ρ_s is soil grain mineral density, τ is shear stress of the plume acting locally on the soil, g is gravity, d_{80} is the soil grain diameter larger than is larger than all the particles comprising 80% of the mass of the soil (the particle size typically used in erosion calculations), c is a measure of soil cohesion, and U is a parameter having units of velocity that must be obtained empirically, whose physical meaning has not been identified. For transition regions of the plume 0.01<Kn<1 this is reduced by multiplying with the experimentally derived rarefaction factor

$$f_R = 130.09\,\mathrm{Kn}^2 + 1.3453\,\mathrm{Kn} + 0.9735 .$$

The factor is an unverified extrapolation beyond 0.1<Kn so results are preliminary until additional experiments extend the range of confidence. Note that erosion rate by a rocket exhaust becomes insignificant when Kn is very large, so the errors are not unbounded.

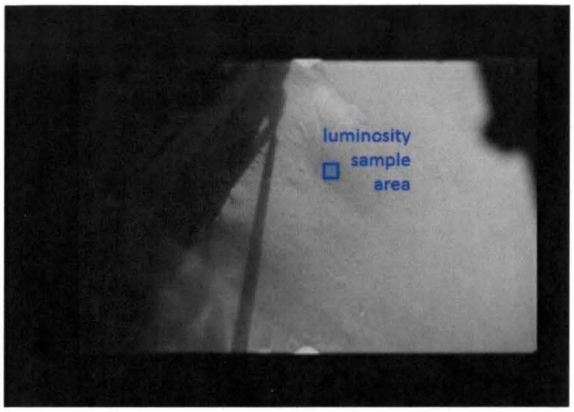
Modeling Methods: Several methods have been developed to model rocket exhaust blowing lunar soil, but none yet has the ability to include all the relevant physics. Models that neglect particle lift tend to underpredict particle ejecta velocities since particles are not lifted as efficiently into the faster, denser portion of the ground jet. Models that neglect particle collisions fail to predict scattering and the momentum cascade among particle sizes. Simulations imply that collisional processes with a full and correct particle size distribution are important. Note that Immer, et al [1] concluded that the ejecta that struck Surveyor III from the Apollo 12 landing was just scattered particles, the main ejecta sheet passing above Surveyor III. However, simple scaling arguments imply that collisional processes are spatially restricted so that single particle trajectory models are relatively accurate when beyond the initial erosion annulus. This method correctly predicts ejecta velocities and angles observed in Apollo landing videos. Models that neglect 2-way coupling may overpredict erosion rates, but these shall be empirically derived until more complete codes are developed.

Flux Predictions: The above scaling relationship can be used in conjunction with plume gas modeling software to predict erosion rate during a lunar landing scaled by the unknown factor U, which can then be determined by summing up the flux within the field of view of the Apollo landing videos and comparing with the observed optical density of the blowing dust. The scaling relationship can then predict ejecta flux for other vehicles with different thrust and landing profiles. This has been performed for spacecraft representing the Google Lunar X-Prize (GLXP) competitors, and the impingement of ejecta flux on the Apollo sites, which the GLXP competitor missions will be visiting. Based on these predictions, a landing distance of 2 km has been recommended by NASA to reduce – but not eliminate – the damage to these sites.

Dust Levitation: A dust cloud is observed hovering around the Apollo sites after the engine is shut off from landing and again after the LM ascent stage has departed. It may be lofted by electrostatics since rocket exhaust is positively charged.

A plot comparing luminosity changes observed in video images for the descent and ascent cases shows the dust cloud dissipation occurs on similar time scales. These effects may contaminate mission instruments but may also provide insight into electrostatic properties of the dust.

Apollo 15: Descent



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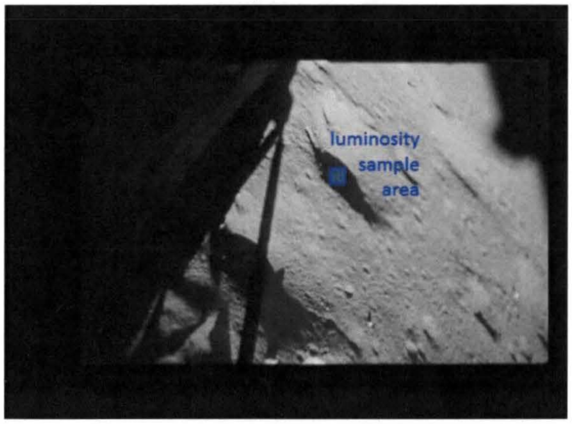

Figure 1. View from Apollo 15 after engine cutoff. (Top) Immediately after engine cutoff. (Bottom) Long time (>30 sec) after engine cutoff.

Regolith Disturbance: Images of the regolith under the Lunar Modules show that the soil was stripped away by the plume in well-defined layers, possibly the geological strata. This implies that there are mechanical discontinuities at the strata boundaries. We hypothesize that these are due to micrometeoroid gardenting, penetrating to a depth of only 1 or 2 mm to form a skin that resists the plume, while the strata themselves are on the order of 1 or 2 cm thick with less resistance to the plume.

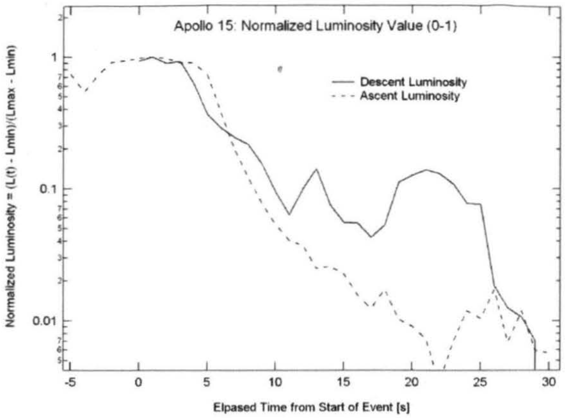

Figure 2. Dust clearing in Apollo 15 ascent compared to descent.

References: [1] Immer, C. D., et al (2011), *Icarus*, 211,1089-1102.